FUNCTIONALLY-GRADED NPR (NEGATIVE POISSON'S RATIO) MATERIAL FOR A BLAST-PROTECTIVE DEFLECTOR

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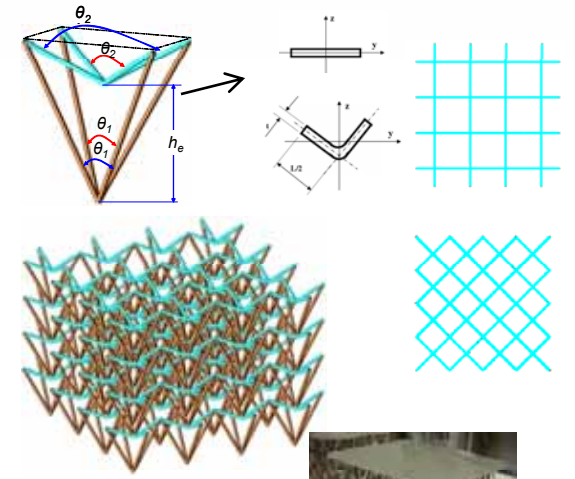
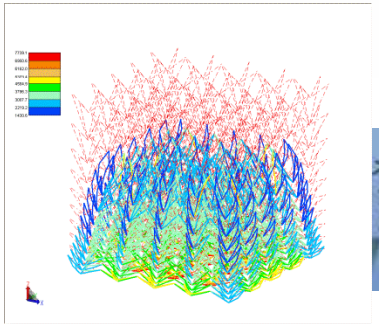
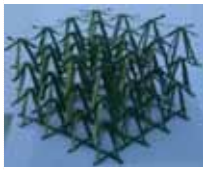
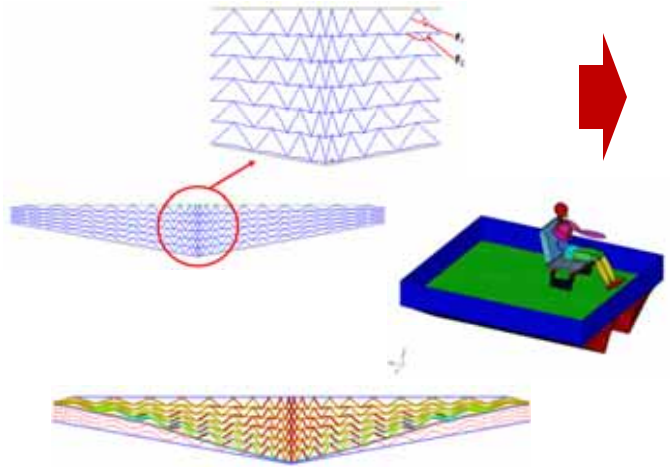
Presentation Outline



NPR



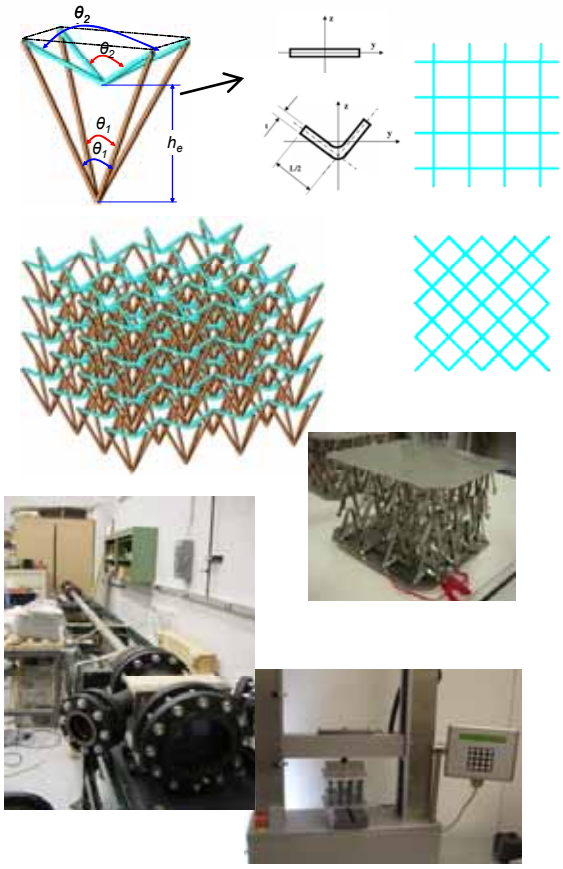




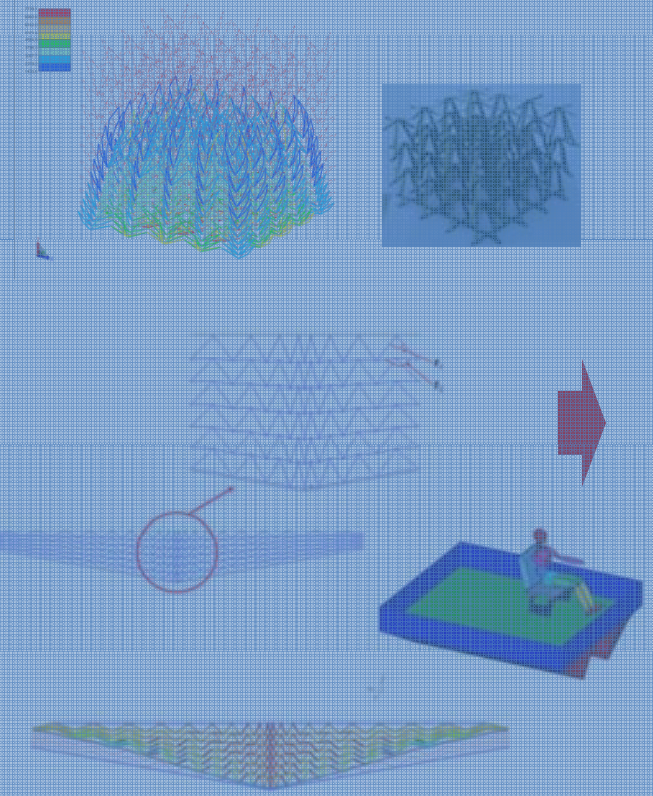
Functional and Functionally-graded NPR

Application to blast protection

Presentation Outline



NPR

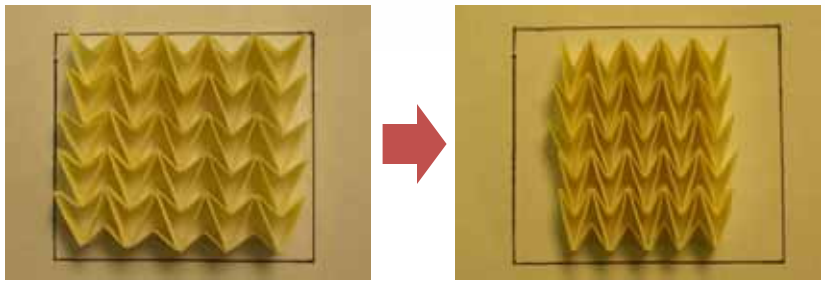


Functional and Functionally-graded NPR

Application to blast protection

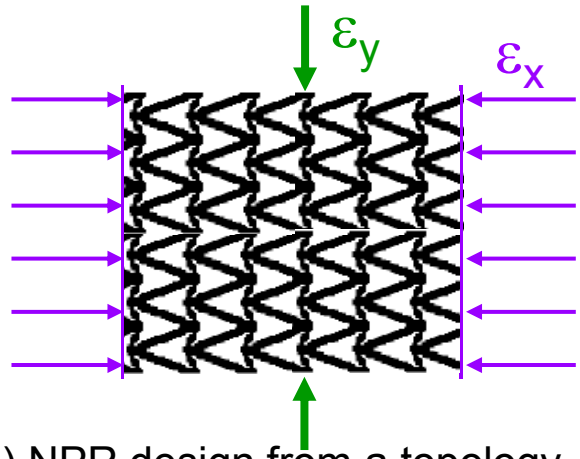
Negative Poisson's Ratio (NPR) Material

- *NPR materials* first introduced in 1987 (Lakes, *Science*)
- Unlike conventional materials, NPR materials may shrink when compressed along a perpendicular direction.
- Engineered NPR material concept obtained from a topology optimization process (Larsen, 1997)
- Extended to three-dimensional NPR design (patent pending)



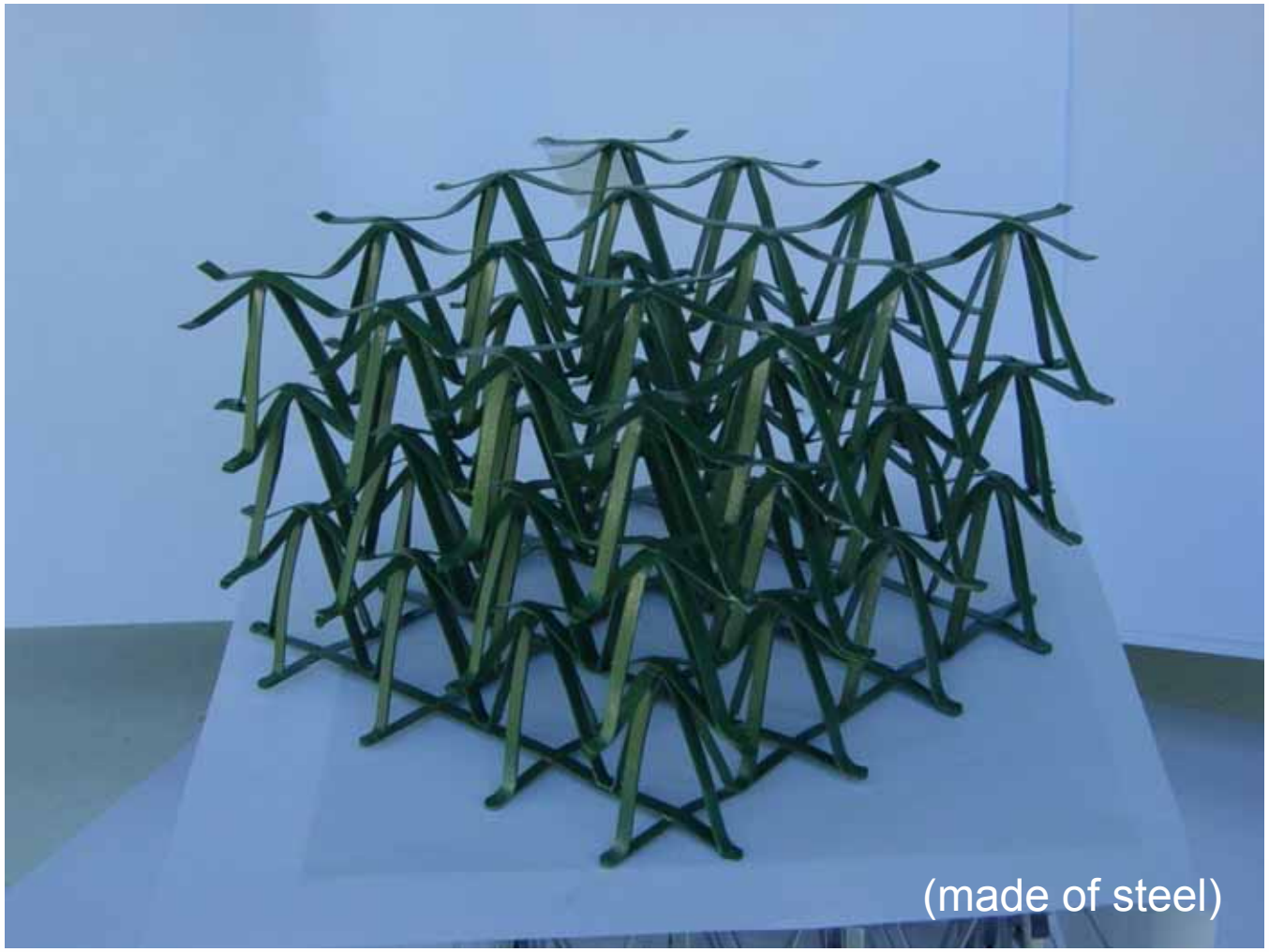
Original shape *Deformed shape*

a) NPR effect

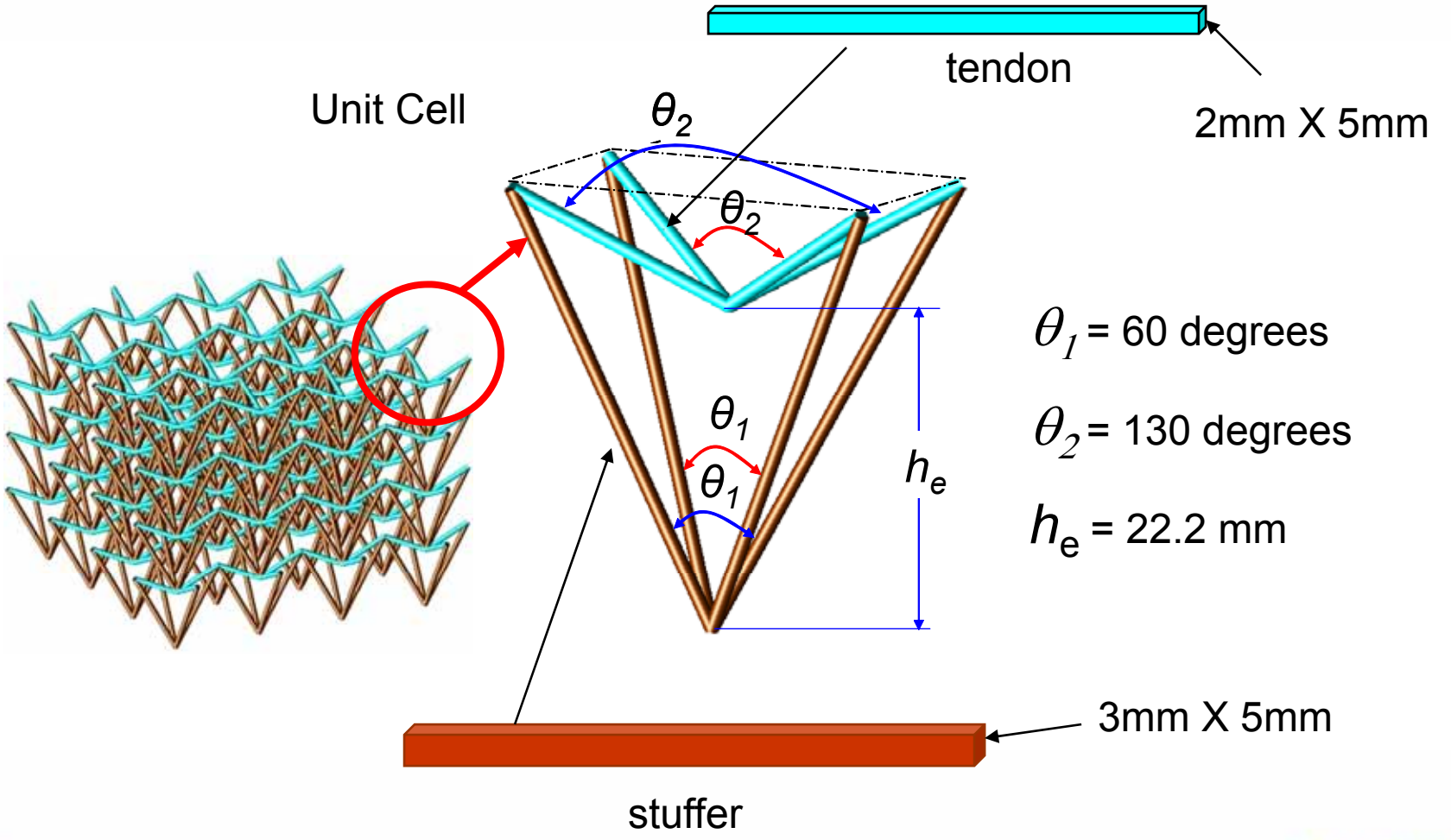


b) NPR design from a topology optimization process (Larsen 1997)

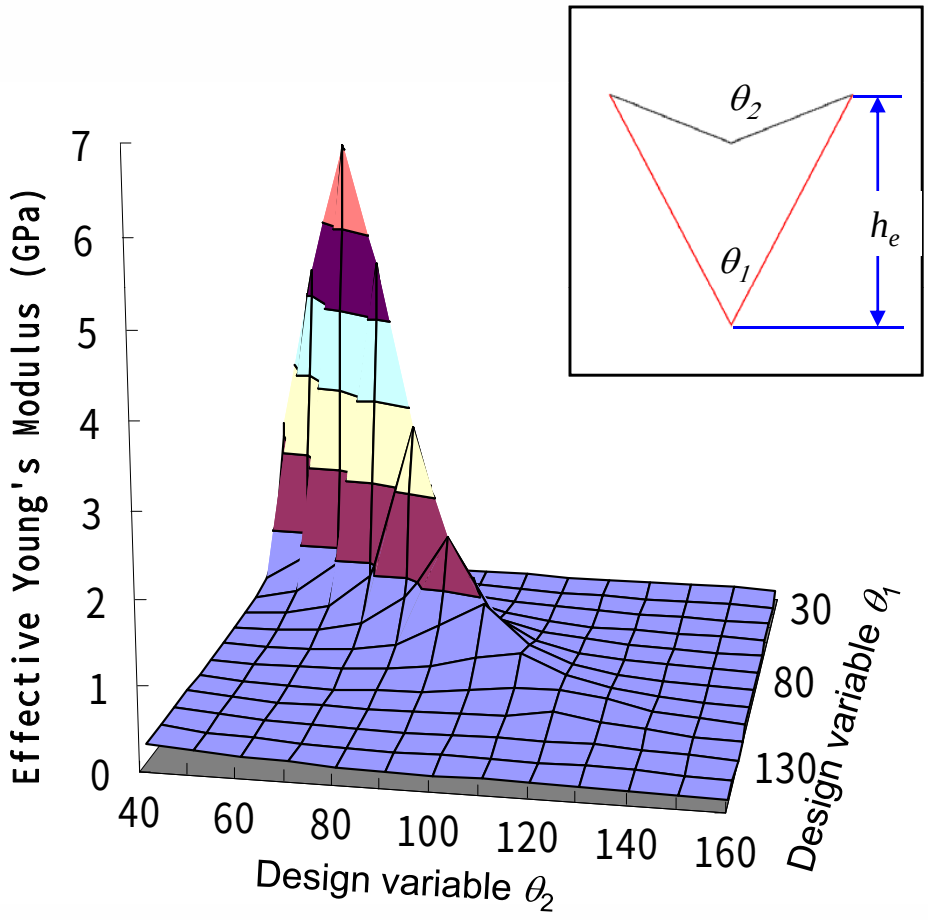
Three-Dimensional NPR Material (MKP Patent Pending)

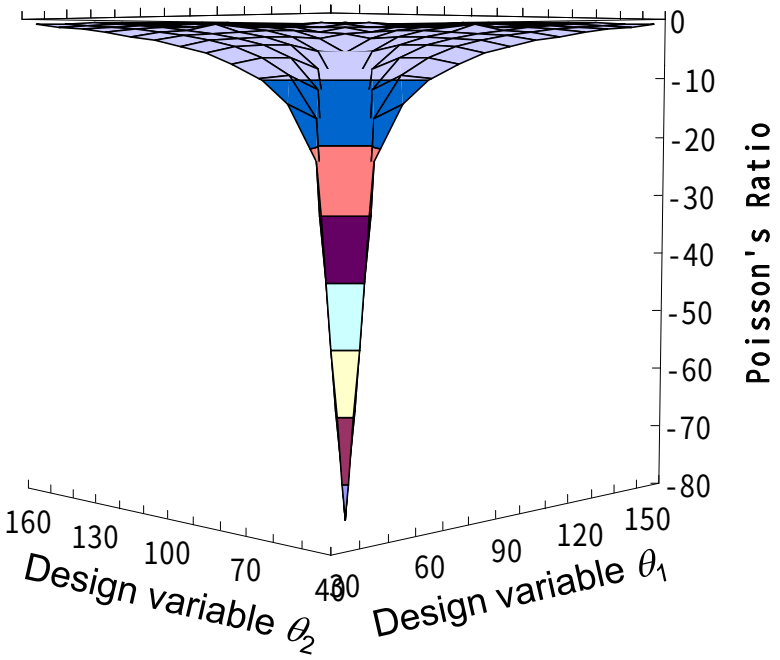


Design Variables



Effective Material Properties



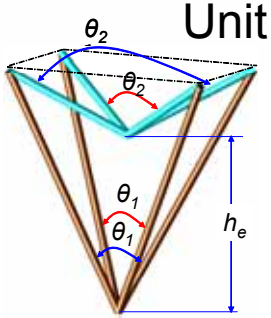


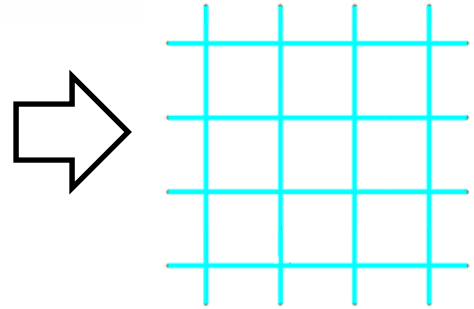
Effective Young's Modulus

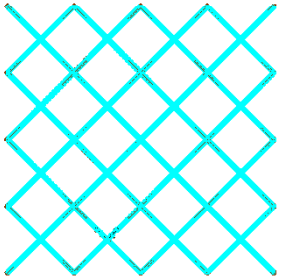
Effective Poisson's Ratio

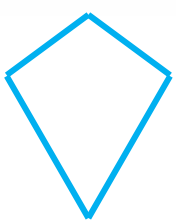
Variations of Arrangement

Unit Cell

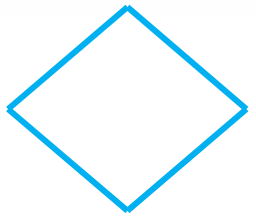




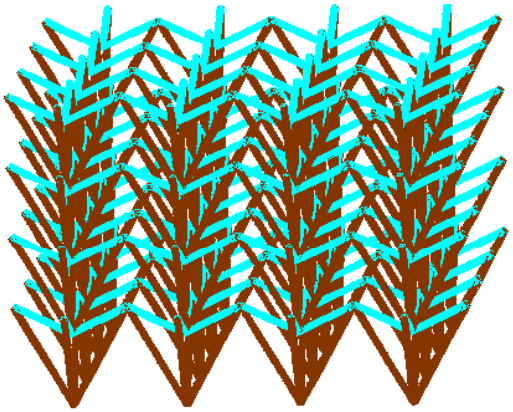




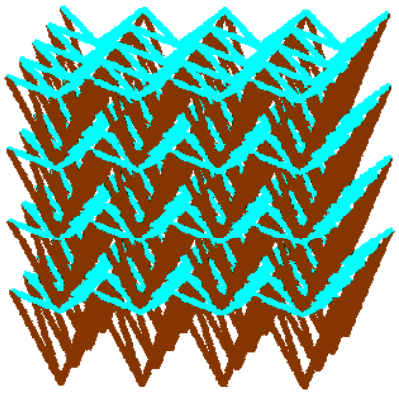
PPR-1



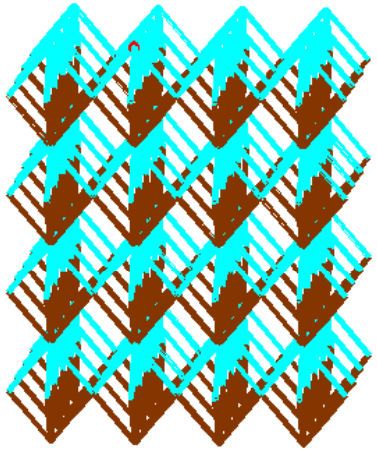
PPR-2



Parallel Configuration
(NPR-p)

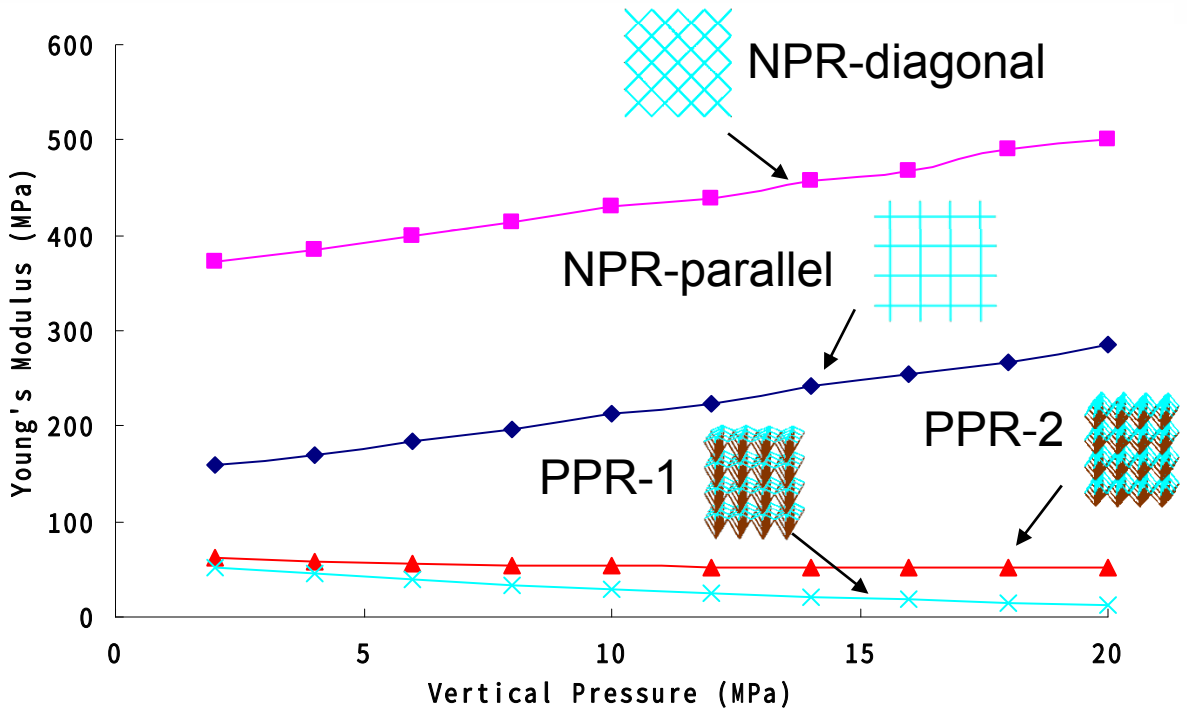


Diagonal configuration
(NPR-d)



PPR configuration
(PPR-1/PPR-2)

Stiffness Comparison of NPR & PPR Materials

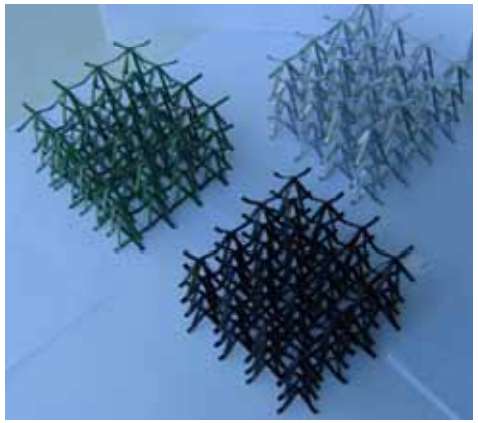


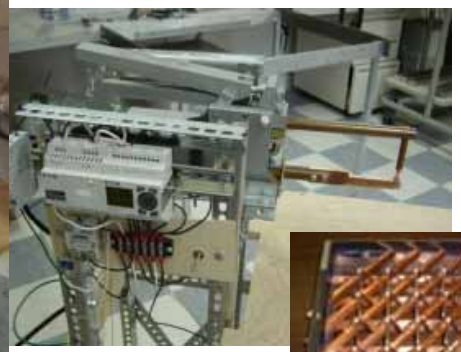
- NPR materials are much stiffer and stronger than PPR materials
- When normal pressure increases
  - Stiffness of NPR material increases
  - Stiffness of PPR material decreases
- NPR diagonal material
  - Is the strongest
- NPR parallel material
  - Is the second strongest

- Young's Modulus with respect to normal pressure
- Same weight and same area density (area density of the NPR-diagonal is 2X)

Manufacturing Process for Coupons Development

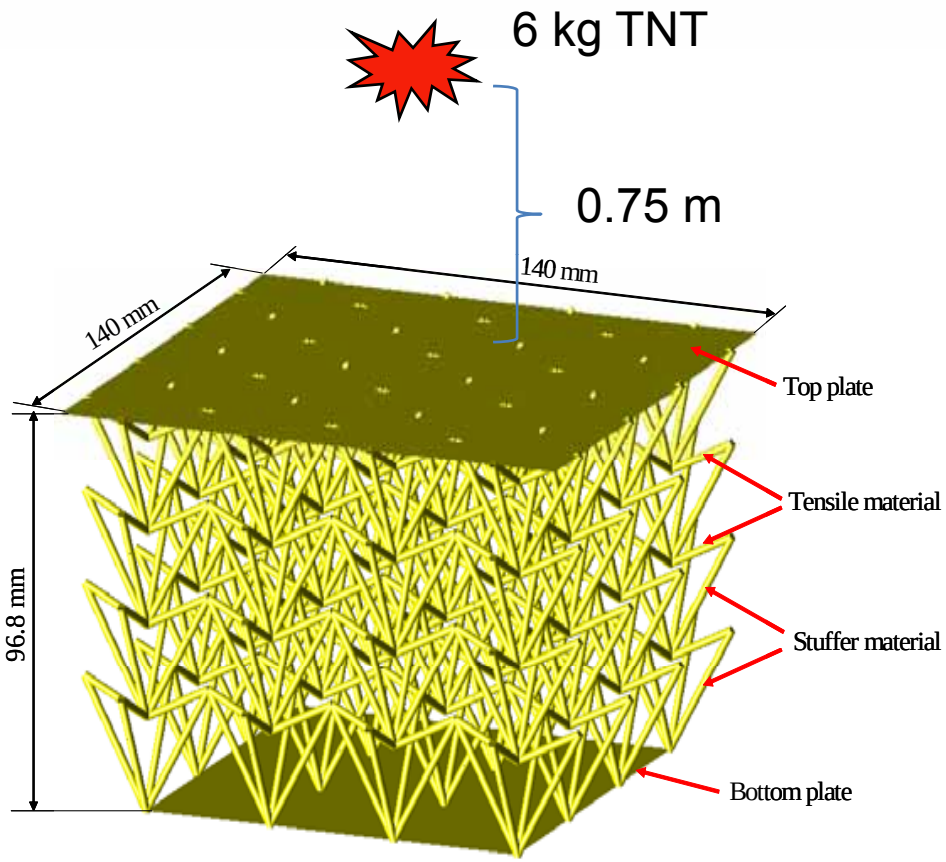
Manufacturing process





- Prove manufacturability and fabrication method
- Develop testing specimens

Virtual Blast Testing



Parameters:

TNT: 6kg with offset 75cm

Material: Steel

Tensile: 2.0 mm x 2.0 mm

Stuffer: 2.0 mm x 4.0 mm

Plate thickness: 3.0 mm

Theta 1: 60 deg

Theta 2: 130 deg

Cell unit periodicity in x: 4

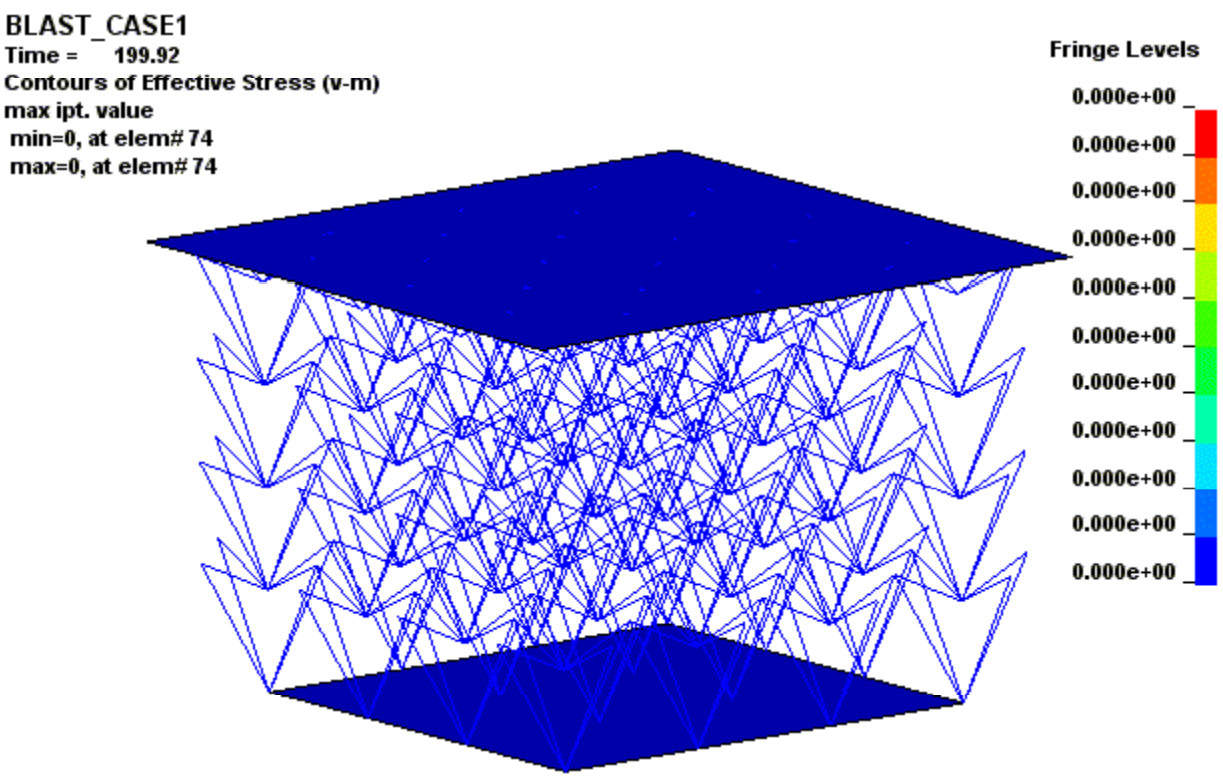
Cell unit periodicity in y: 4

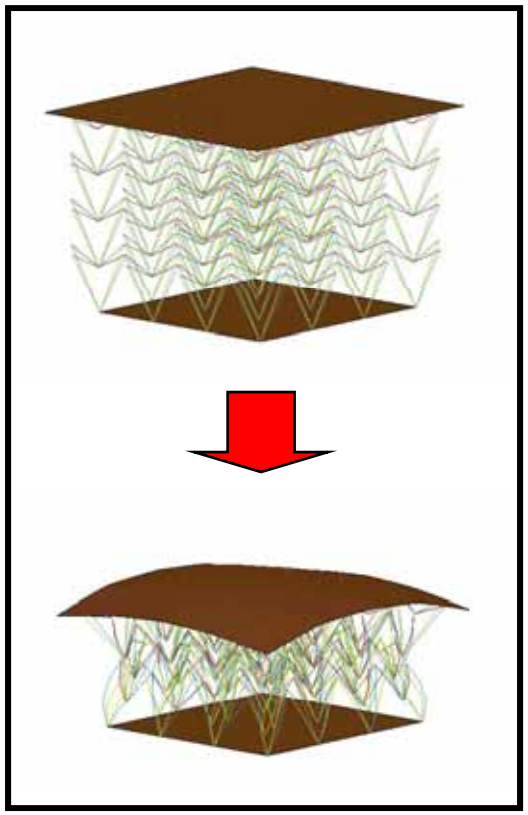
Cell unit periodicity in z: 4

Damping: 0.1%

BCs: nodes on bottom plate no displacement in vertical direction

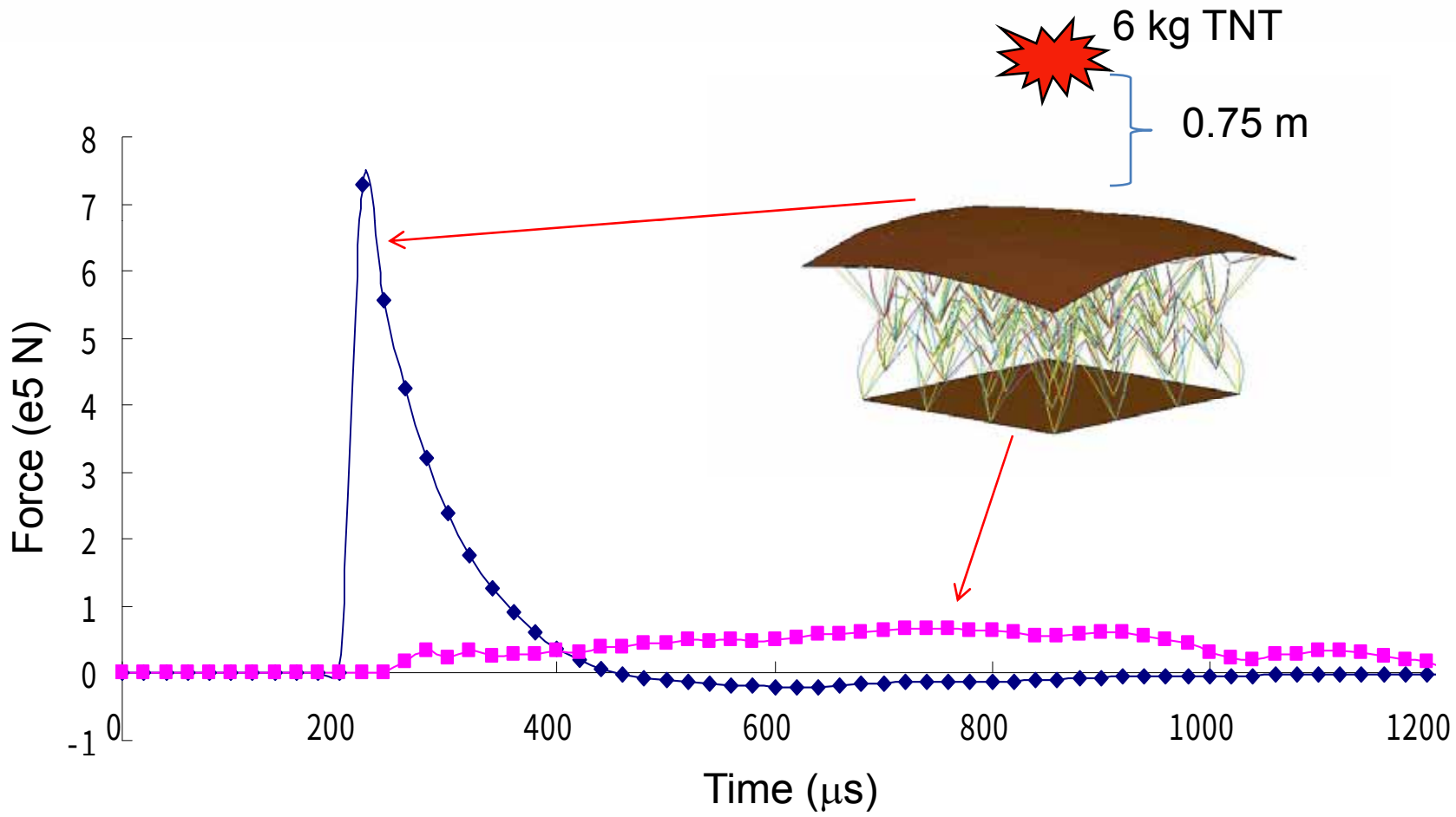
Simulation Result





Deformation and effective Von Mises stress on the top plat (in Mbar)

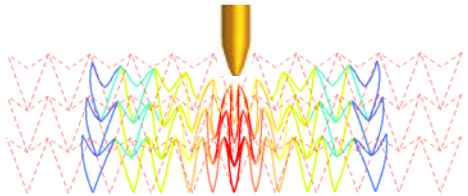
Blast Force Mitigation



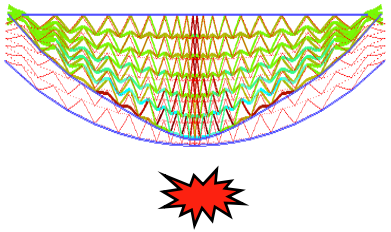
Unique Features of the NPR Material

MSTV
MODELING AND SIMULATION, TESTING AND VALIDATION

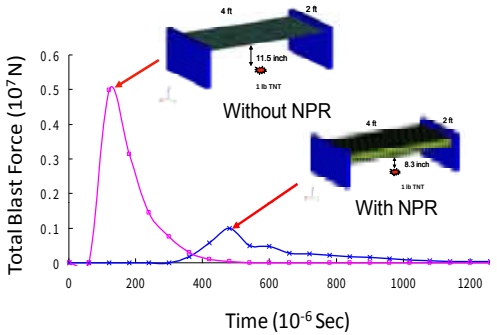
- Basic Features of the *NPR (Negative Poisson's Ratio)* Material:



Material concentration

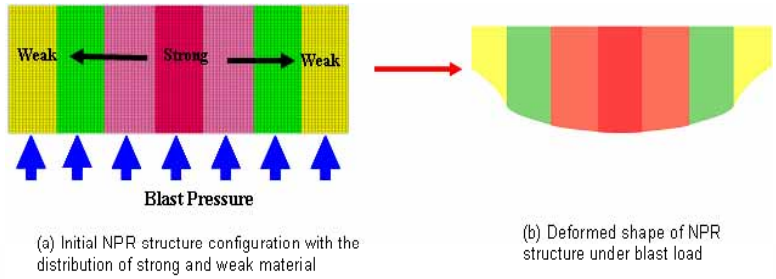


Bulging effect



Impact force mitigation

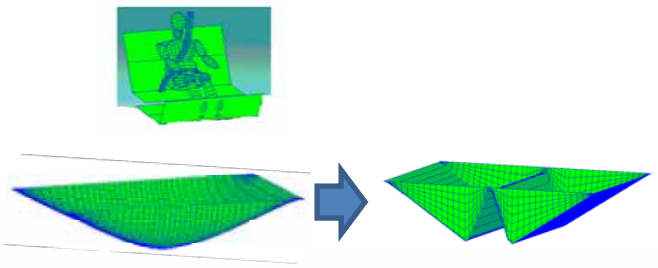
- *Functional and Functionally-Graded* Design



(a) Initial NPR structure configuration with the distribution of strong and weak material

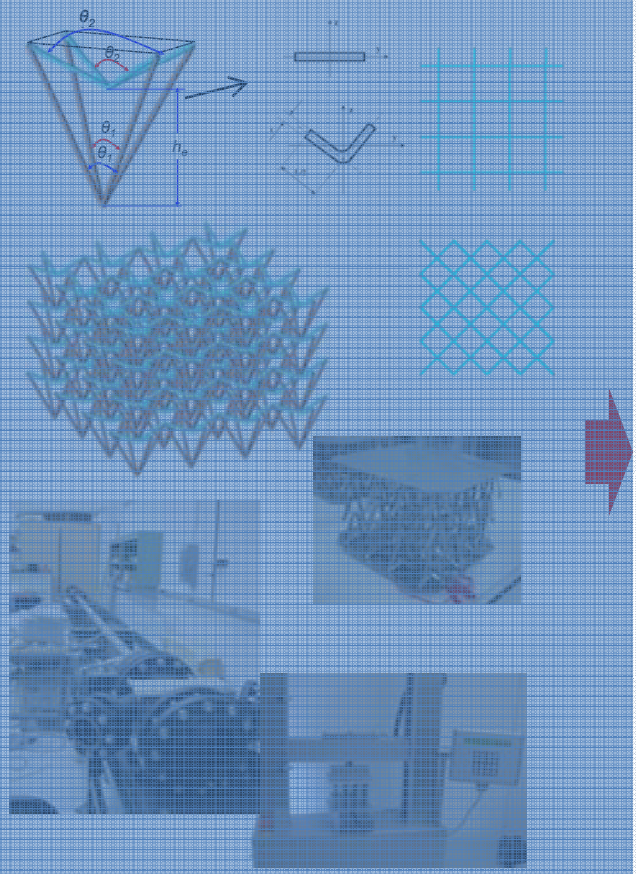
(b) Deformed shape of NPR structure under blast load

Adaptive Shape Change

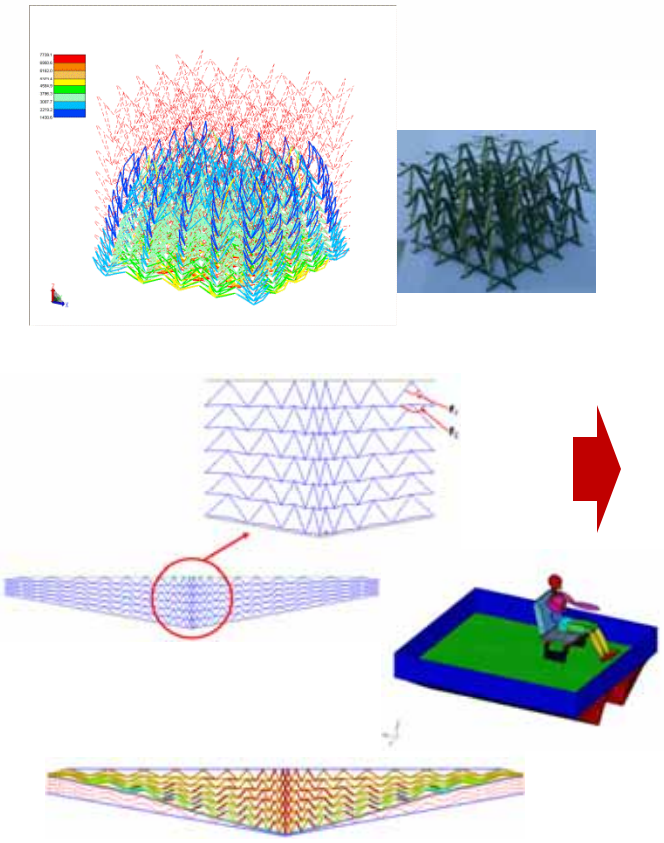


Optimal Shape Design

Presentation Outline



NPR

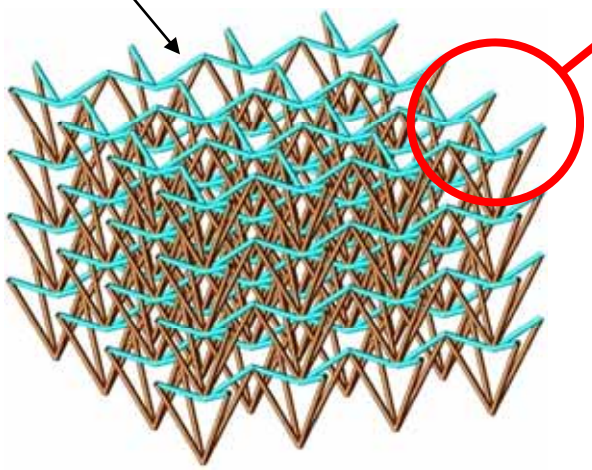


Functional and Functionally-graded NPR

Application to blast protection

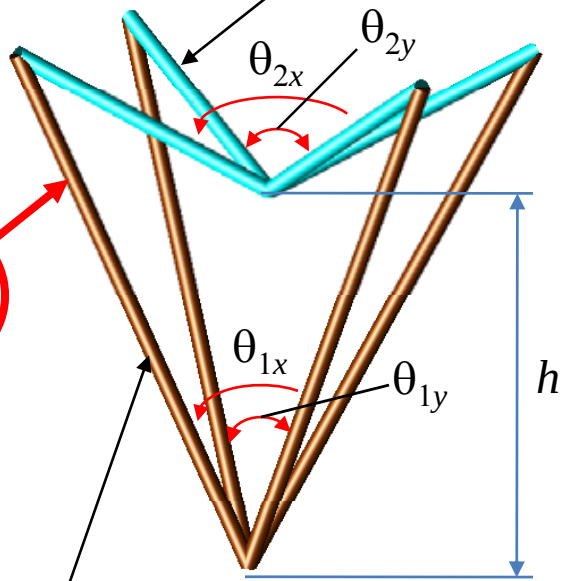
Generalized Design Variables

- Various filling materials
- Or no filling



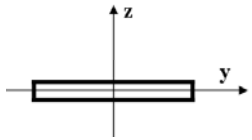
Tendon

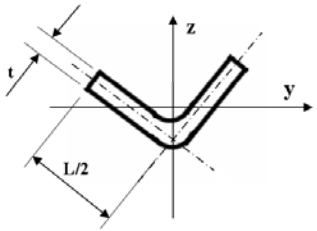
Unit Cell



Stuffer

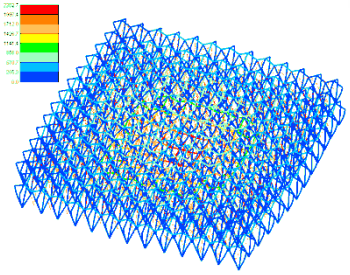
- Metallic strip
- Cable
- Organic fiber
- …

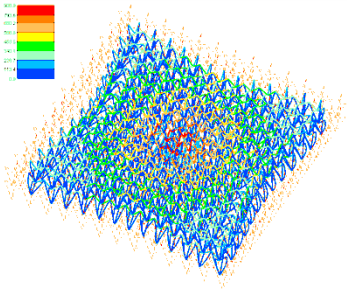


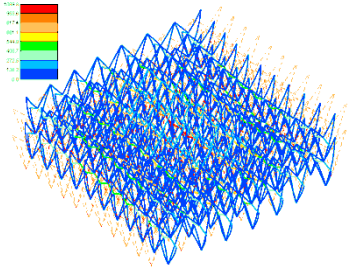


- Various geometry shapes and raw material selections

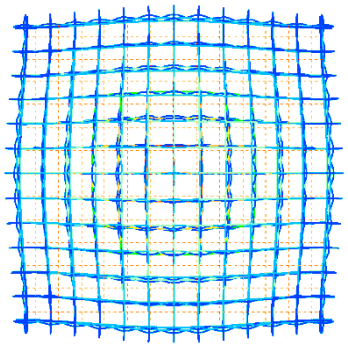
NPR by Design



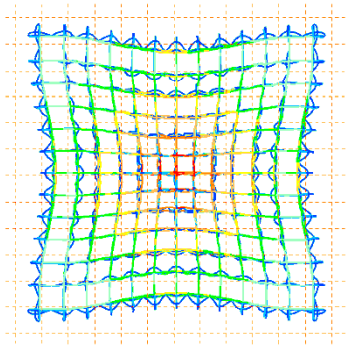




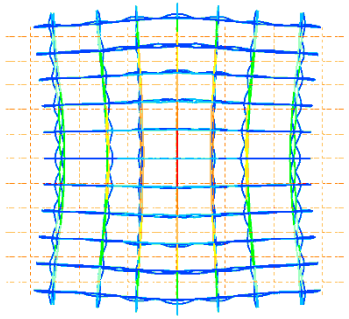
PR(Y) = 0.7



PR(Y) = -2.5



PR(Y) = 1.80



PR(X) = 0.7

θ_{2x} = -110°
θ_{2y} = -110°

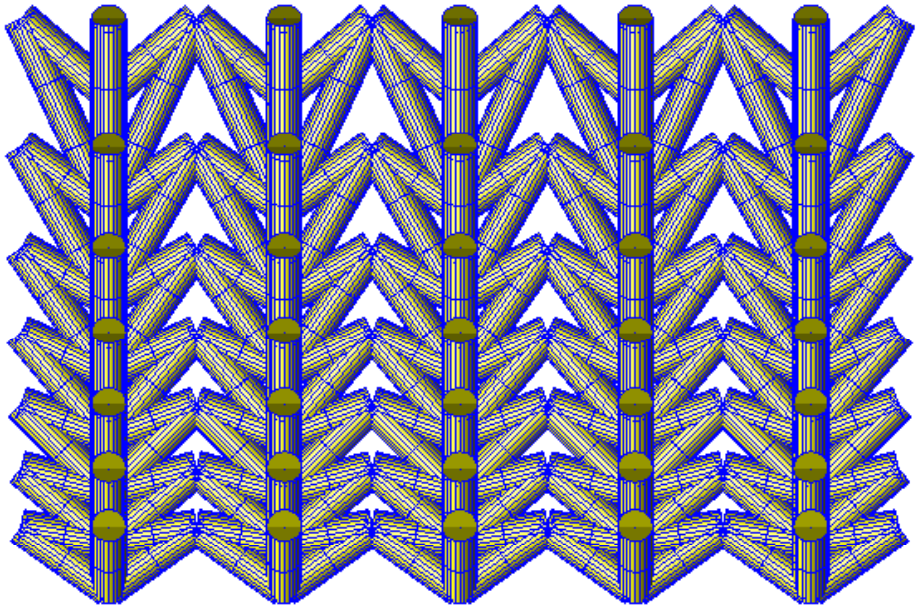
PR(X) = -2.5

θ_{2x} = 110°
θ_{2y} = 110°

PR(X) = -8.3

θ_{2x} = 90°
θ_{2y} = -110°

Functionally-Graded NPR



Layer 7: E = 4.5e3MPa, $\nu = -0.79$

Layer 6: E = 3.8e3MPa, $\nu = -0.50$

Layer 5: E = 3.2e3MPa, $\nu = -0.31$

Layer 4: E = 2.7e3MPa, $\nu = -0.18$

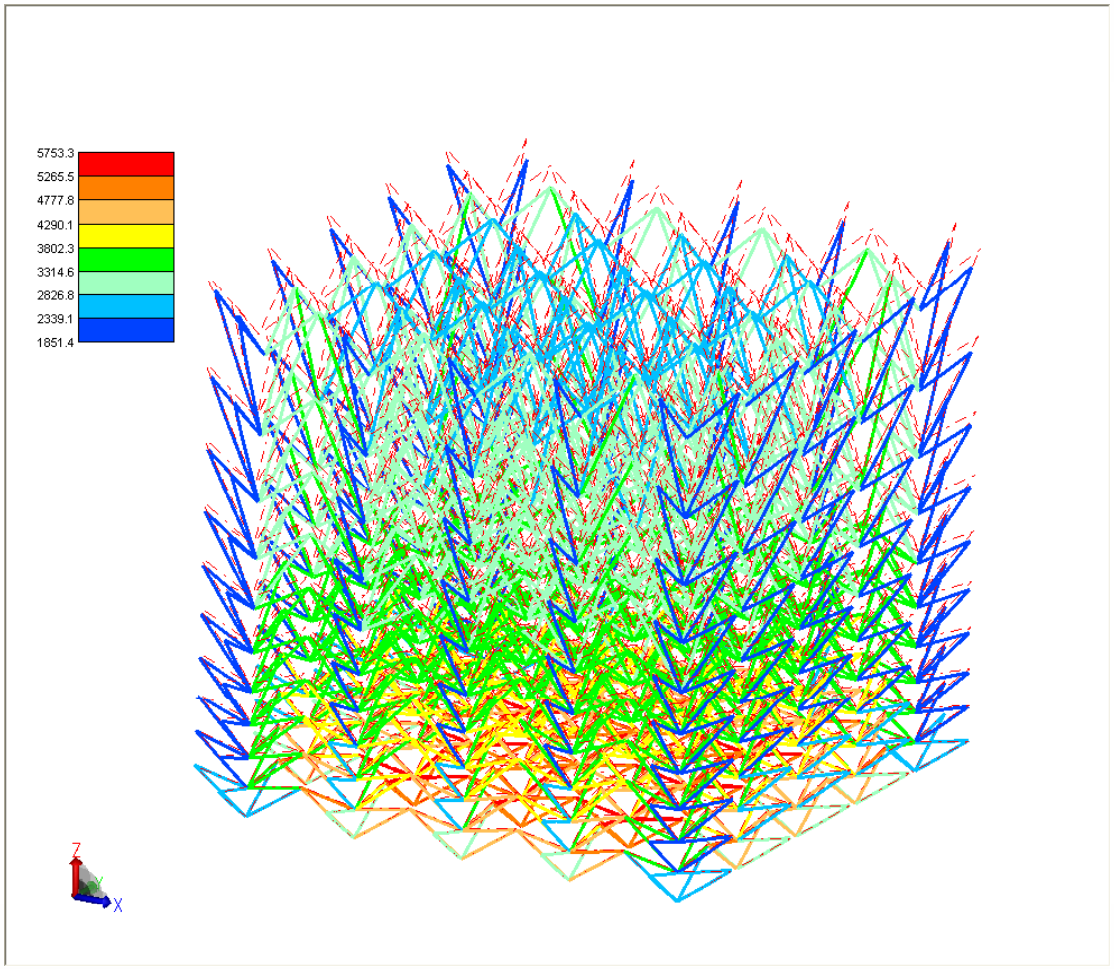
Layer 3: E = 2.1e3MPa, $\nu = -0.10$

Layer 2: E = 1.7e3MPa, $\nu = -0.04$

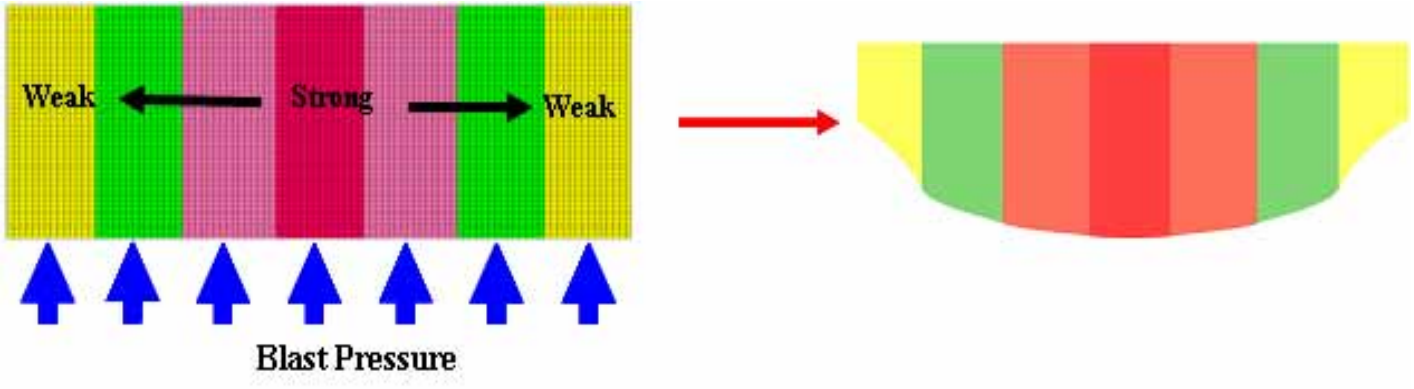
Layer 1: E = 1.3e3MPa, $\nu = 0$

The integrated structure's properties are: E = 2.8e3MPa, ν = -0.24

Simulation Result



The "Reactive" Deflector Concept

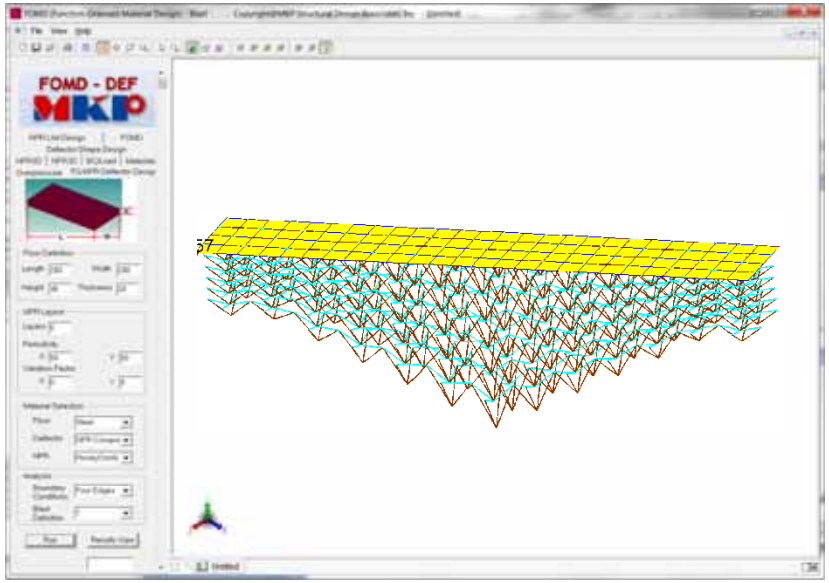


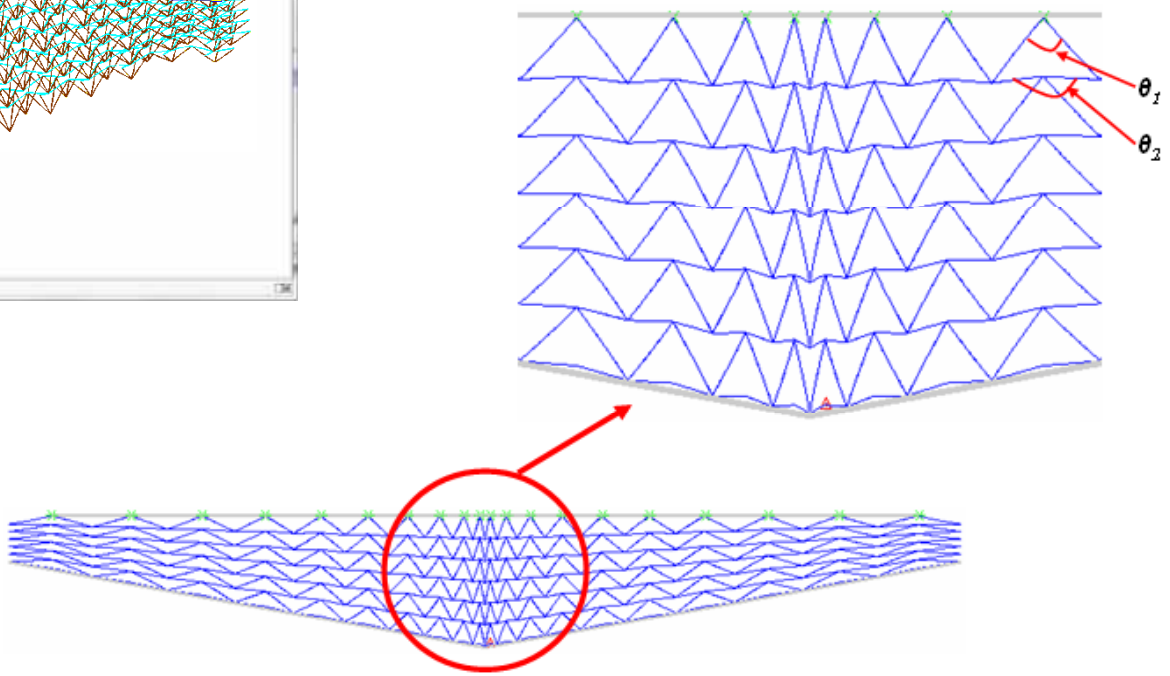
(a) Initial NPR structure configuration with the distribution of strong and weak material

(b) Deformed shape of NPR structure under blast load

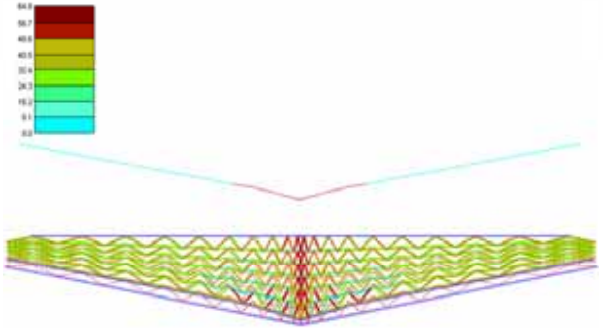
- Based on the bulging effect of NPR material
- Is enhanced by a functionally-graded NPR concept with varied stiffness along the lateral direction

Varied Stiffness Distribution

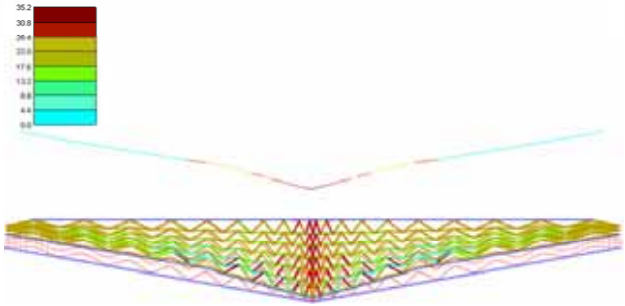




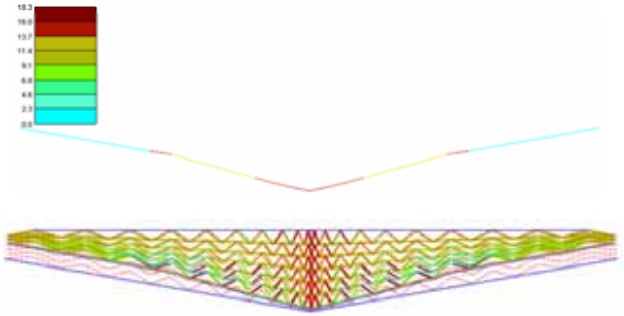
Adaptive Structure for Blast Protection



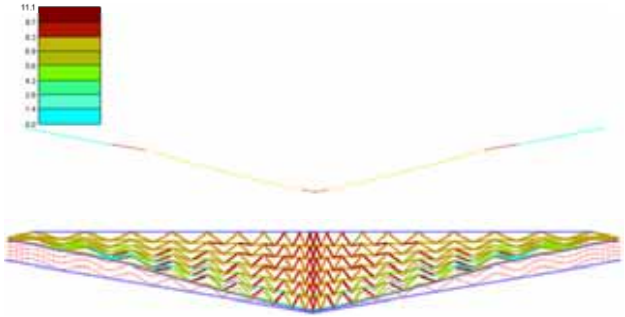
a) T1=150 μs



b) T2=210 μs

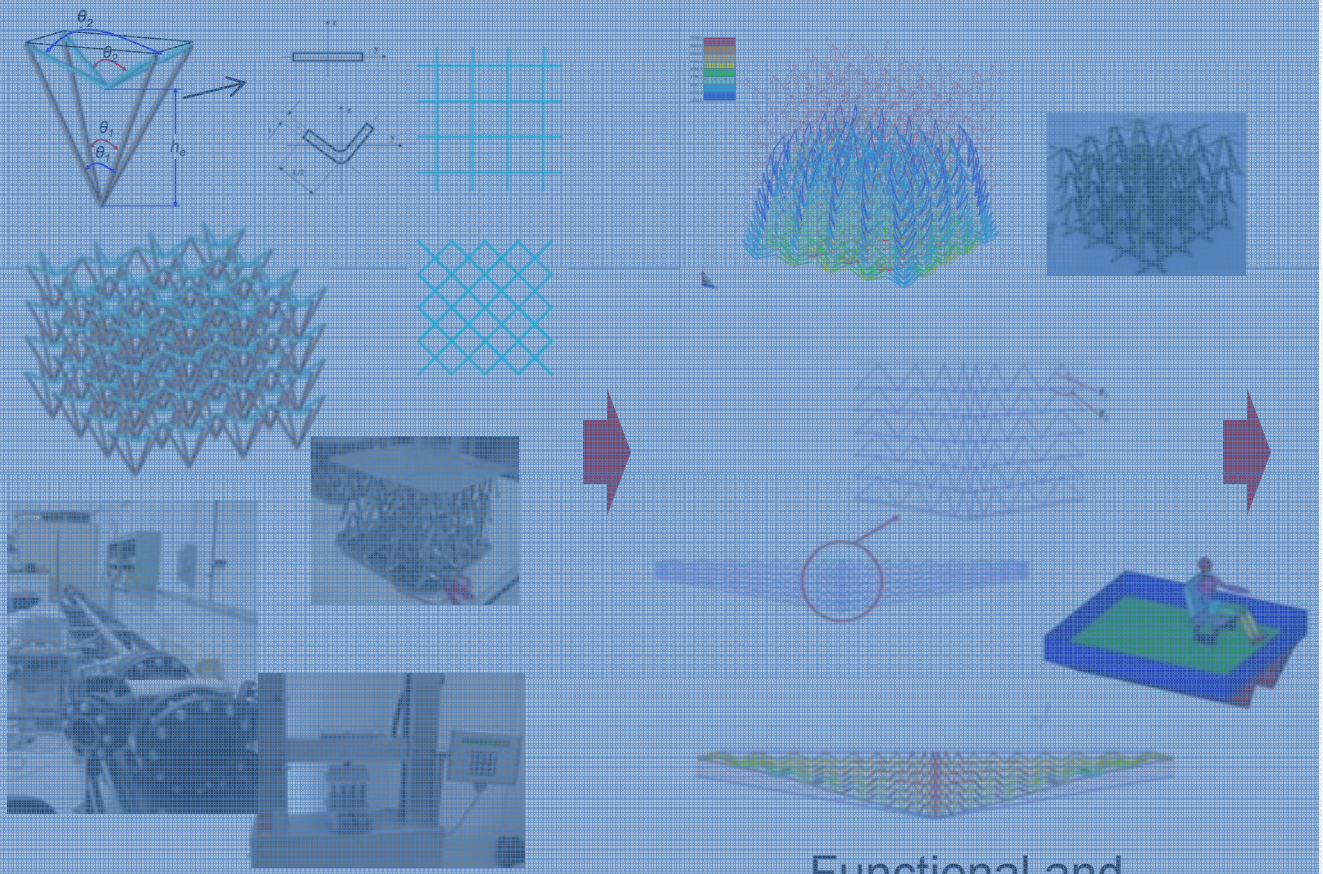


c) T3=270 μs



d) T4=330 μs

Presentation Outline



NPR

Functional and Functionally-graded NPR

Application to blast protection

Objective

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MODELING AND SIMULATION, TESTING AND VALIDATION

- Develop an innovative structural-material concept for a novel deflector that can significantly improve crew protection under explosives with minimum vehicle weight and C.G. height
  - New structural-material configuration, which can react to the blast of explosives and improve protection by adaptively changing material configuration
  - Maximize blast protection
  - Minimize vehicle weight
  - Minimize vehicle C.G. height
  - Can be functionally designed

Accomplishments

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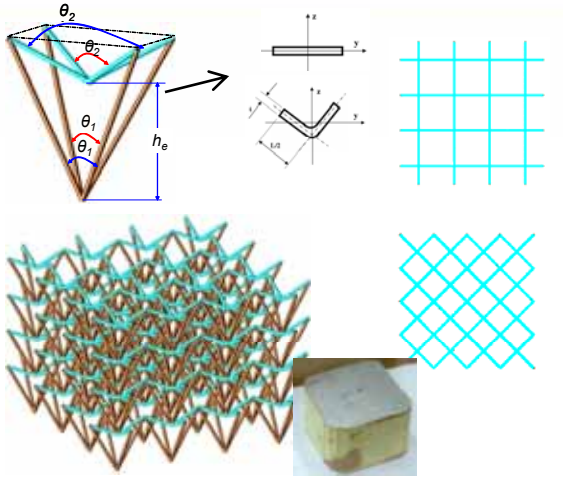
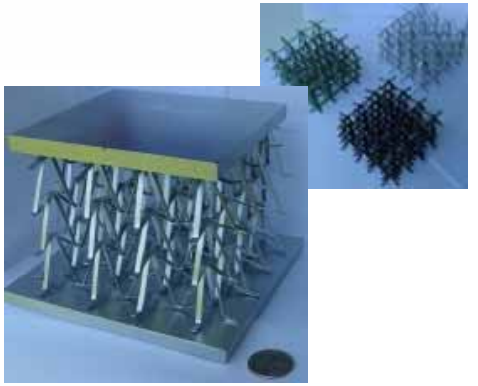


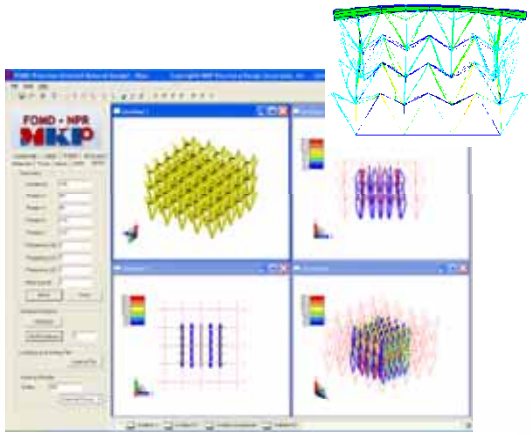
Concept development

Manufacturing process

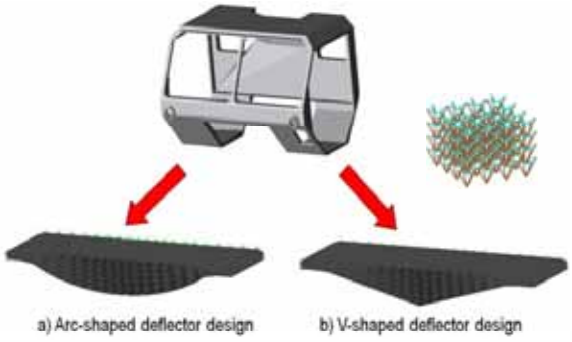


Prototyping

Mechanical & blast tests

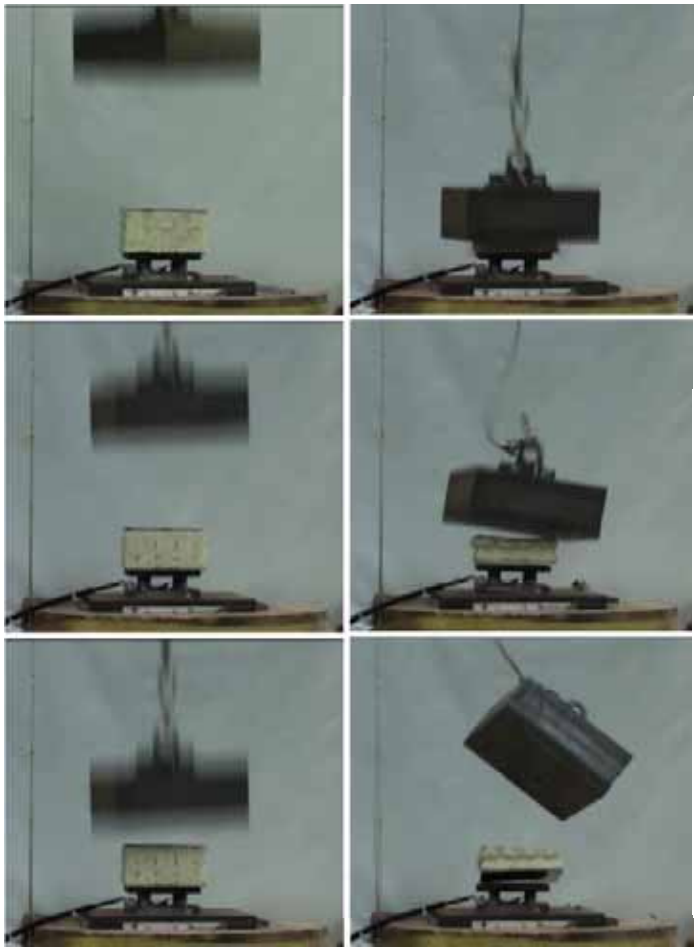


New design capabilities



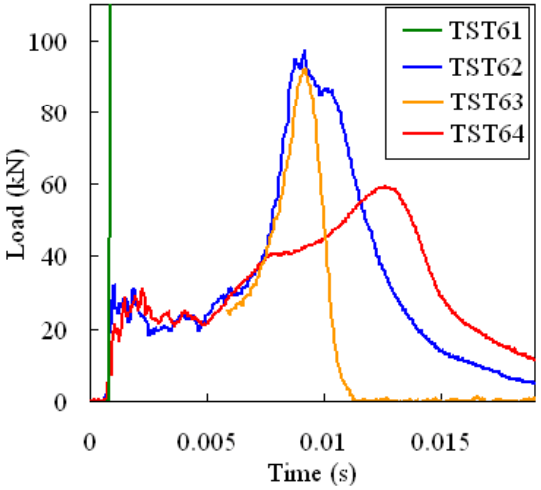
Design optimization

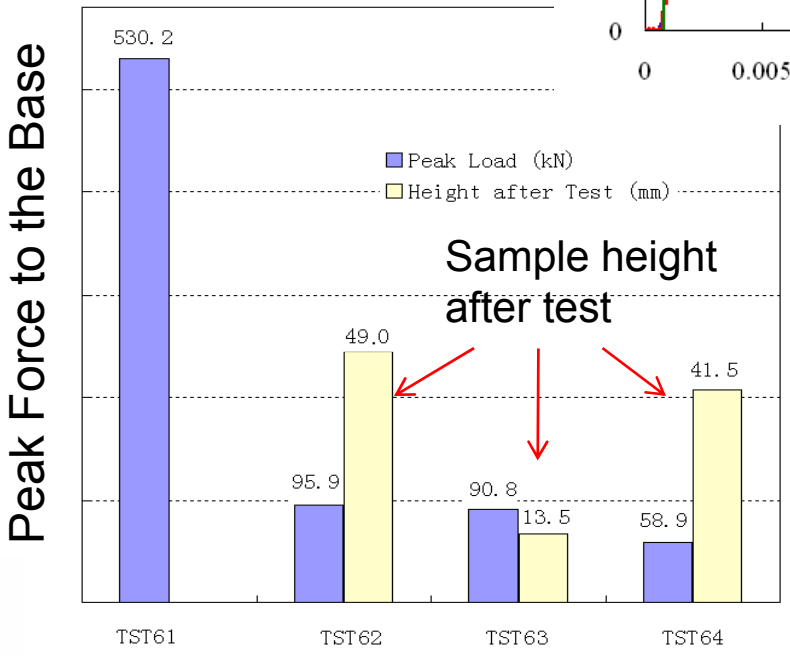
Drop Tower Tests

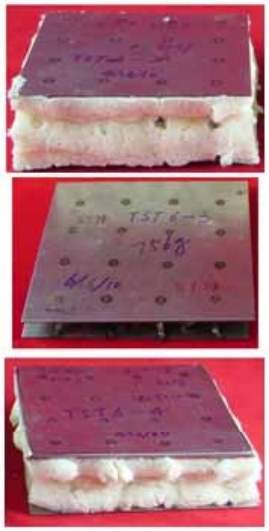


A 50 kg mass from 12 feet height

TST61: without NPR
TST62: FG-NPR (1.0/1.2/ 1.8 mm with foam)
TST63: NPR (1.0 mm) without foam
TST64: NPR (1.0 mm) with foam







Blast Tube Tests: BTR Composite vs. Honeycomb

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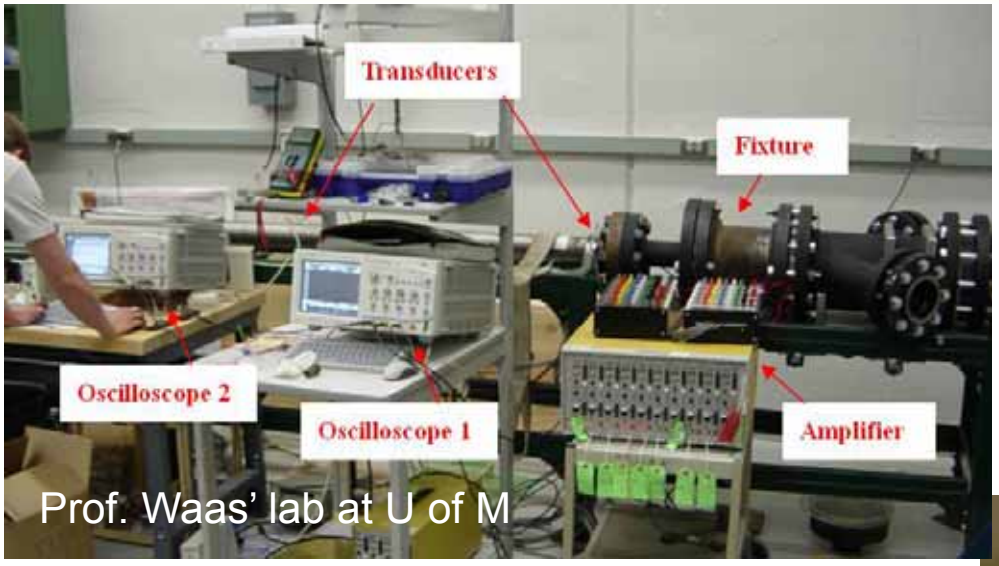
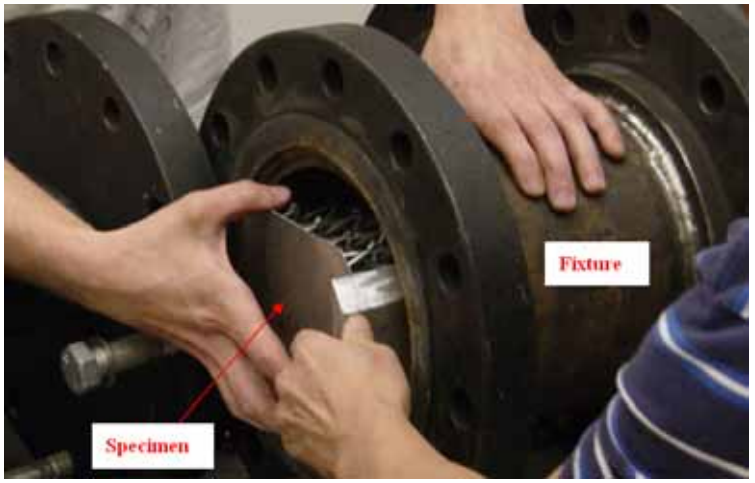
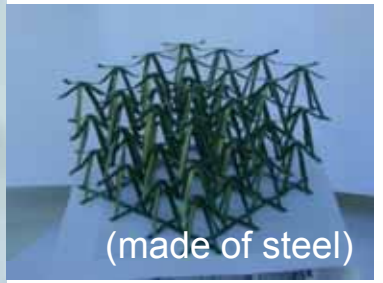


Prof. Waas' lab at U of M



Square honeycomb core panel (HC-1, HC-2): 5.5" X 5.5" X 1.6". Weight: 506 g.

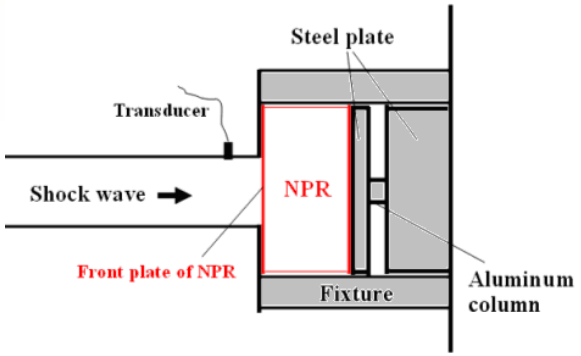

(made of steel)

Geometry of NPR: 5.5" X 5.5" X 3.5",
Weight: without foam: 398g, with foam:540g

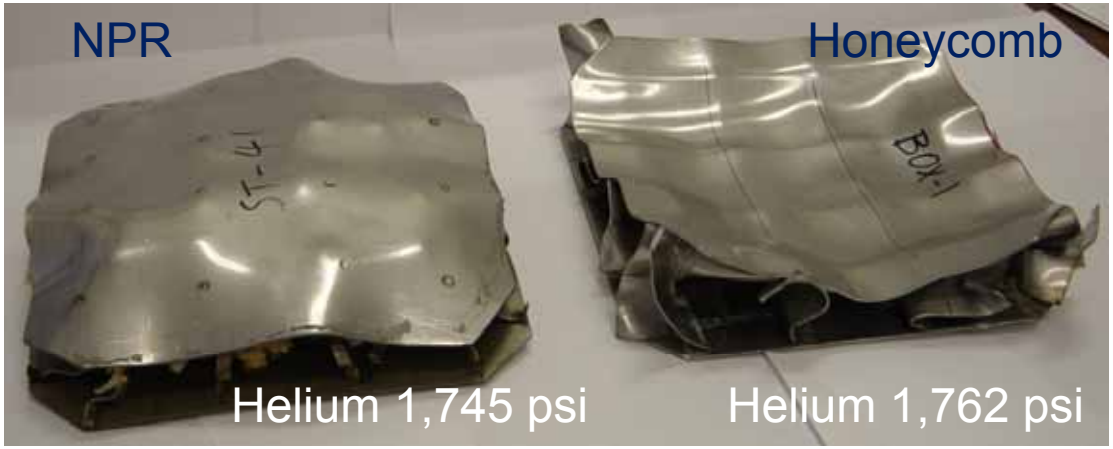
Comparison of NPR with Honeycomb

Geometry of the square honeycomb core: 5.5” X 5.5” X 1.6”,
Weight: 506g.

Geometry of NPR: 5.5” X 5.5” X 3.5”,
Weight: without foam: 398g, with foam:540g



Boundary & loading conditions



- Profiles of specimens after testing
- NPR presents a convex surface, while square honeycomb presents a concave surface

Field Blast Test Plan

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TNT Air Blast Parameter:

Standard test: **6 kg** =13.23 lb

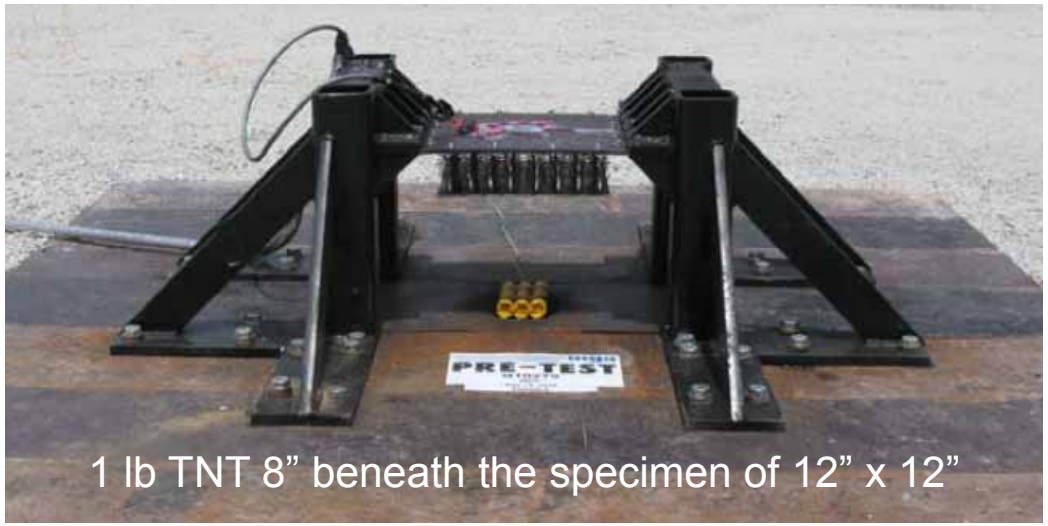
0.5 m = 1.64 ft

Scaled Distance= 0.69 ft/lb$^{1/3}$

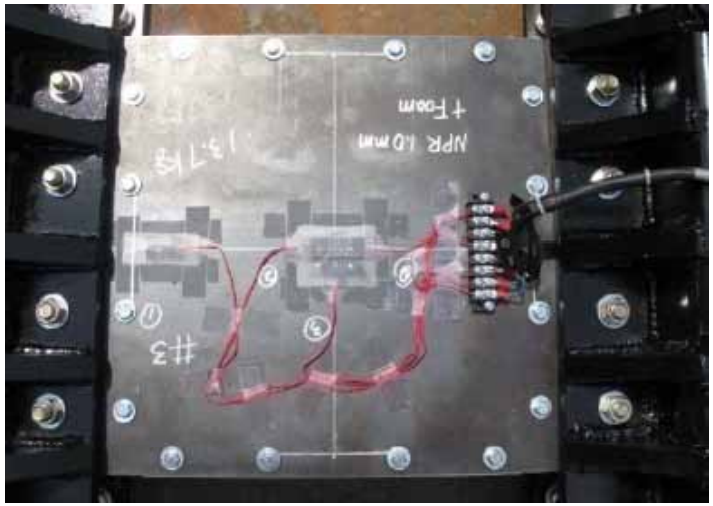
Equivalent Air Blast Parameter:

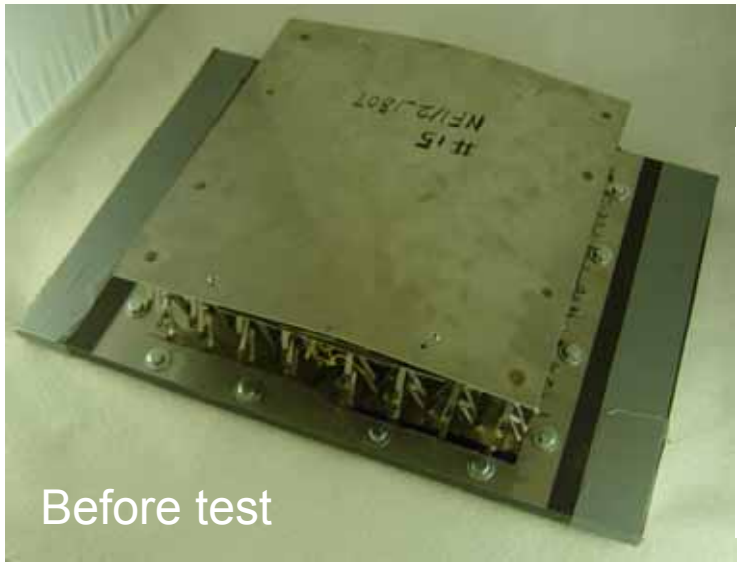
Standard test: **1 lb** and

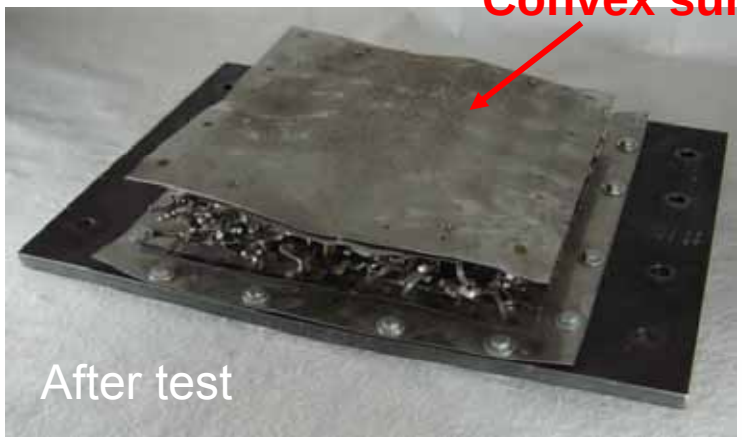
0.69 ft = 21 cm



1 lb TNT 8” beneath the specimen of 12” x 12”



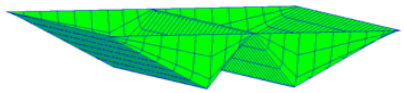

Before test

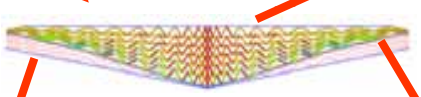

Convex surface
After test

Concluding Remarks

- Three unique features of the NPR material concept-validated by both virtual prototyping and physical tests
  - Material concentration under the load
  - Bulging effect for blast wave deflection
  - Blast force mitigation
- NPR materials many perform much better than regular materials
  - Better stiffness and strength characteristics
  - Better shear resistance – more stable
- Functionally-graded NPR design may provide
  - Shape morphing and material redistribution, and hence better protection performance
  - Less deflector height required for the same level of protection

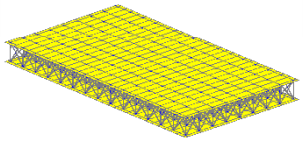
Lightweight, Shape Adaptive Blast Deflector Concept

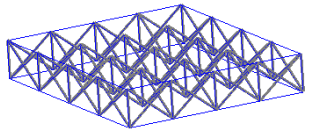




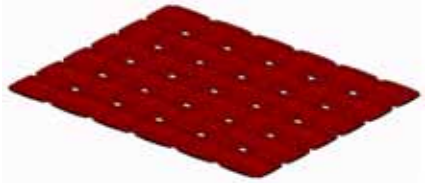
W-shape deflector

V-shape adaptive deflector

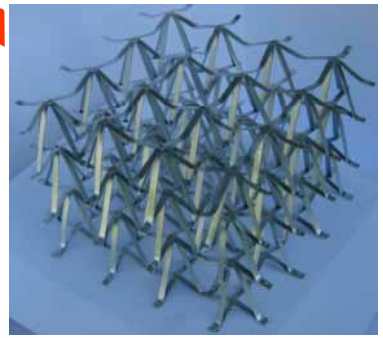


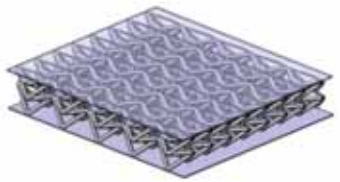


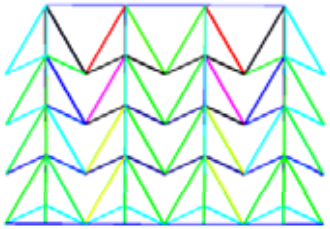
BTR deck/floor plate
(Patent No.: US 7,563,497 B2)



Nanoclay-reinforced composite front plate
(Fiber-reinforced woven composite with nanoclay- reinforced matrix)







NPR adaptive deflector core
(Patent Application No.: US 2010/0119792 A1)